Kaluza-Klein Dark Matter in Universal Extra Dimensions

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The Hunt for Dark Matter
Fermilab
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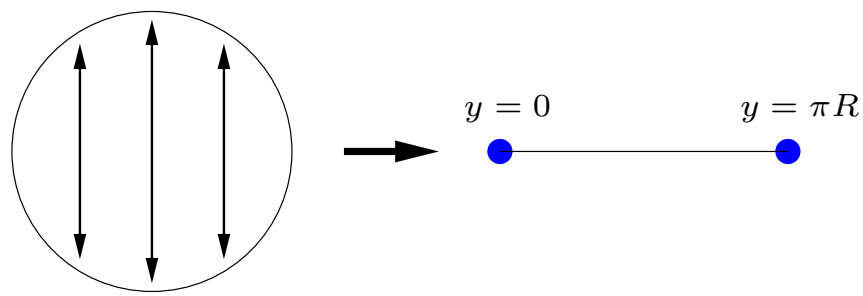
Outline

- Universal Extra Dimensions (5D)
- Revisiting Calculation of Relic Density
- Improved Results
- Two Universal Extra Dimensions: Beyond 5D
- Summary and Discussion

Universal Extra Dimensions

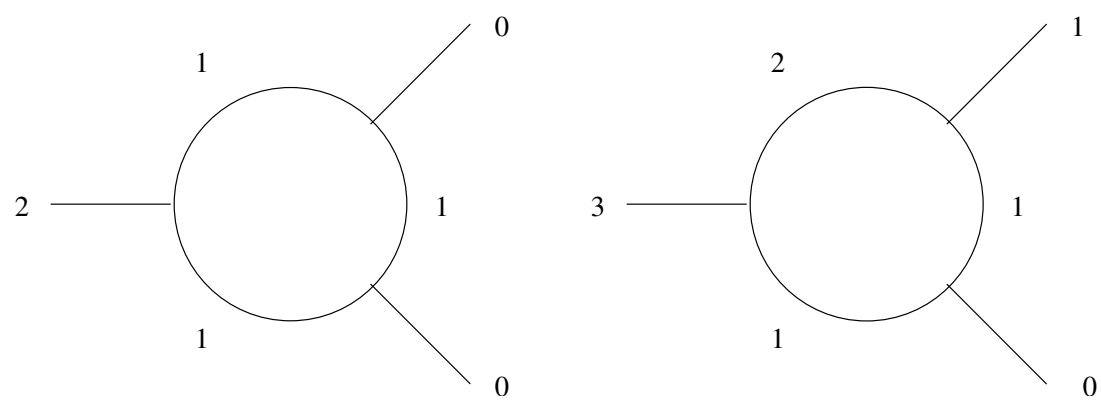
(Appelquist, Cheng, Dobrescu,hep-ph/0012100)

- $S = \int d^4x dy \mathcal{L}_{SM} = \int d^4x \mathcal{L}_{eff}$
- Problem: chiral fermions? too many scalar fields?
- The ED is not really a circle, but orbifold S_1/Z_2:



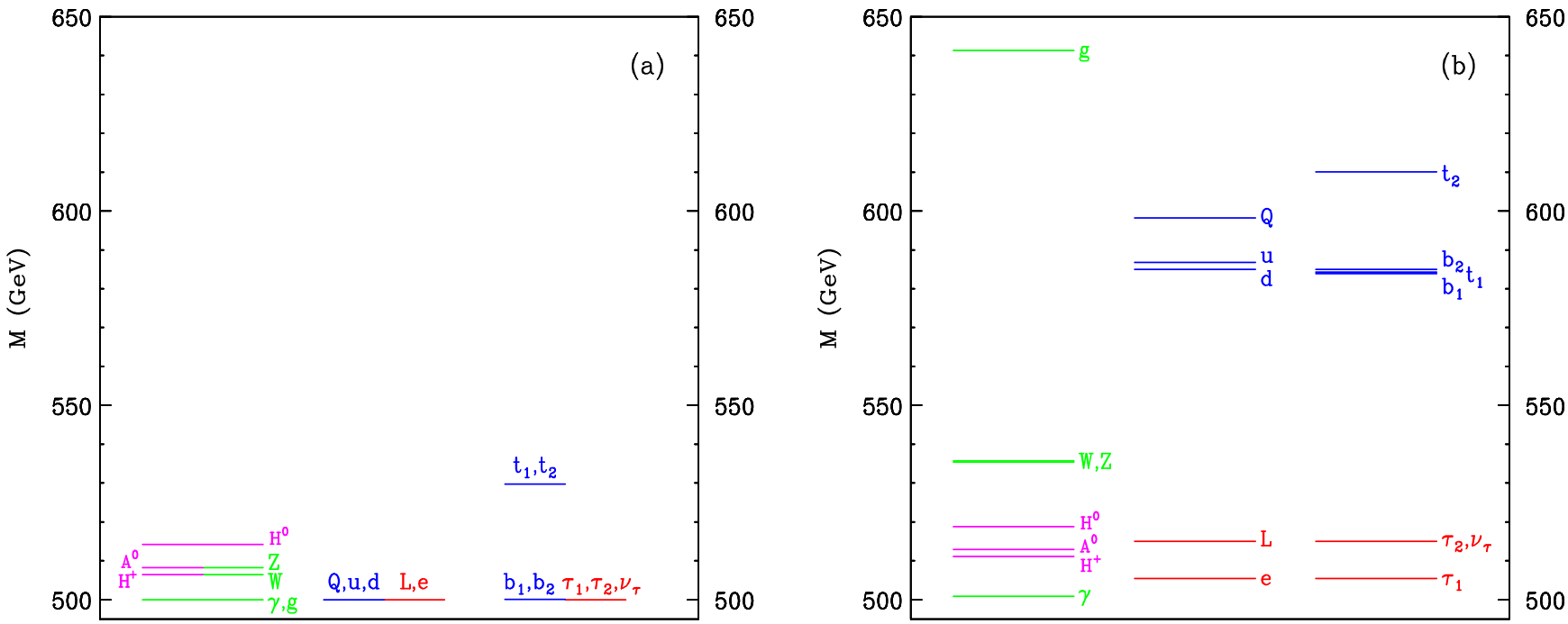
$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \left(\phi^n(x^\mu) \cos\left(\frac{ny}{R}\right) + \chi^n(x^\mu) \sin\left(\frac{ny}{R}\right) \right)$$

- Bulk interactions: conserve KK number $\Leftarrow p_y$ conservation
- Loop corrections generate boundary terms which break KK number n down to KK parity $(-1)^n$



Mass Spectrum : Tree level and radiative corrections

(Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)



- Tree level mass $m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2}$, e_1 is stable $\cdots$
- Radiative corrections are important !
- All but LKP decay promptly $\longrightarrow$ missing energy signals

Relic density

- Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)$$

- Relic abundance

$$\Omega_\chi h^2 \approx \frac{1.04 \times 10^9}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{a + 3b/x_F}$$

- Non-relativistic velocity expansion: $\sigma = \sigma(\gamma_1 \gamma_1 \to SM)$

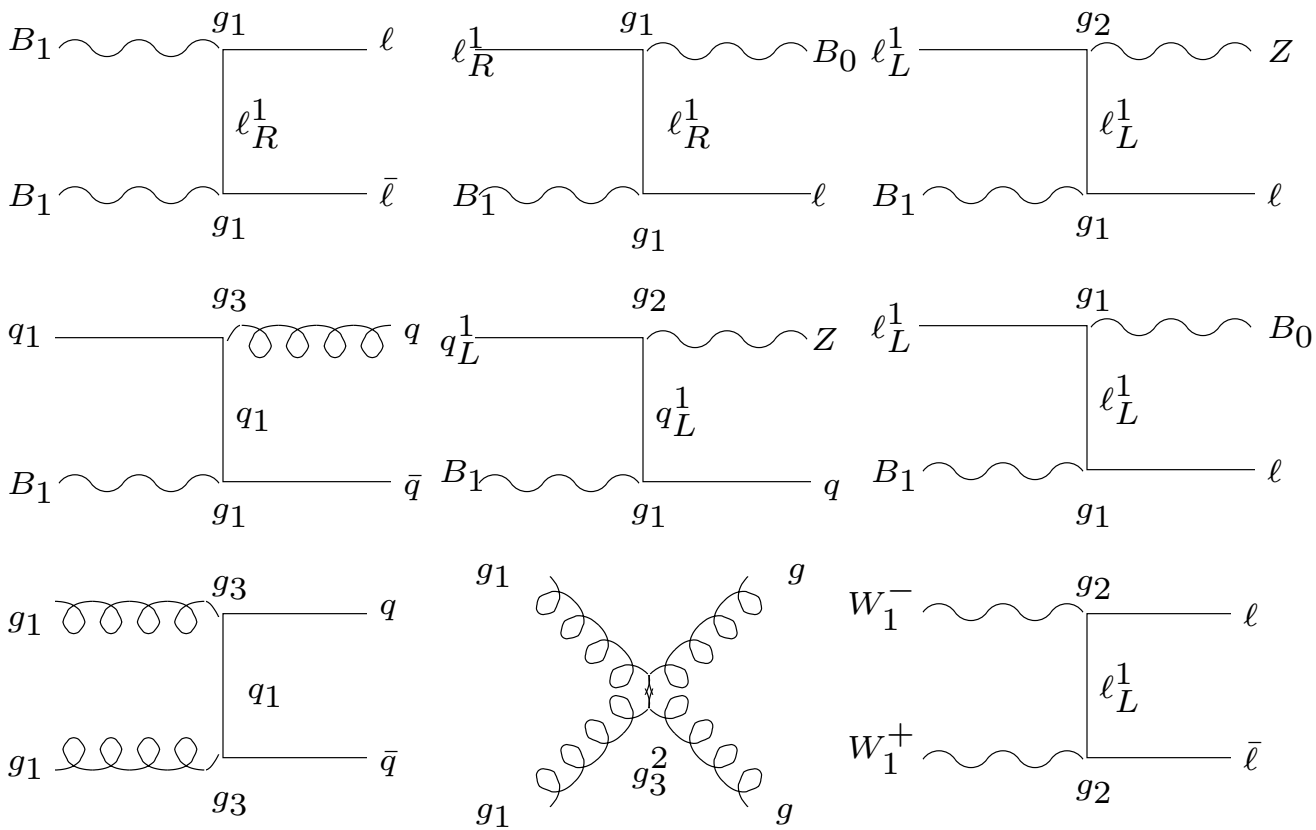
$$\langle \sigma v \rangle = a + b\langle v^2 \rangle + \mathcal{O}(\langle v^4 \rangle) \approx a + 6b/x + \mathcal{O}\left(\frac{1}{x^2}\right)$$

- $\langle \sigma v \rangle \to \langle \sigma_{eff} v \rangle = a_{eff} + b_{eff} \langle v^2 \rangle$
- $\sigma_{eff} \sim \sum_i \sigma_i e^{-x\Delta_i}$ where $\Delta_i = \frac{m_i - m_{\gamma_1}}{m_{\gamma_1}}$
  - $m_i >> m_{\gamma_1} \to \Delta_i >> 1 \to$ no coannihilation
  - KK particles are degenerate $\to$ coannihilations are important

Coannihilation processes

- Examples:
  - keep dominant diagrams only
  - $* \; q_1 B1 \to qg \sim \mathcal{O}(g_3^2 g_1^2)$
  - $* \; q_1 B1 \to qB \sim \mathcal{O}(g_1^4)$
  - $* \; q_1 B1 \to qW \sim \mathcal{O}(g_2^2 g_1^2)$

- KK particles
  - KK gauge bosons: B_1, $W_1^{\pm}$, Z_1, g_1
  - KK leptons: ℓ_L^1, ℓ_R^1
  - KK quarks: q_L^1, q_R^1
  - KK higgses: $H_1^{\pm}$, H_1^0, χ_1^0



Relic density: case with coannihilation

- Effective cross section

$$\sigma_{eff}(x) = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{eff}^2} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \exp(-x(\Delta_i + \Delta_j))$$

$$\sigma_{eff}(x)\, v = a_{eff}(x) + b_{eff}(x)\, v^2 + \mathcal{O}(v^4)$$

- Effective degrees of freedom

$$g_{eff}(x) = \sum_{i=1}^{N} g_i (1+\Delta_i)^{3/2} \exp(-x\Delta_i) \ , \qquad \Delta_i = \frac{m_i - m_1}{m_1}$$

- Freeze-out temperature

$$x_F = \ln \left(c(c+2) \sqrt{\frac{45}{8}} \frac{g_{eff}(x_F)}{2\pi^3} \frac{m M_{Pl} (a_{eff}(x_F) + \frac{6 b_{eff}(x_F)}{x_F})}{\sqrt{g_*(x_F) x_F}} \right)$$

$$I_a = x_F \int_{x_F}^{\infty} a_{eff}(x) x^{-2} dx \ , \qquad I_b = 2 x_F^2 \int_{x_F}^{\infty} b_{eff}(x) x^{-3} dx$$

- Relic abundance

$$\Omega_\chi h^2 \approx \frac{1.04 \times 10^9}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{I_a + 3 I_b / x_F}$$

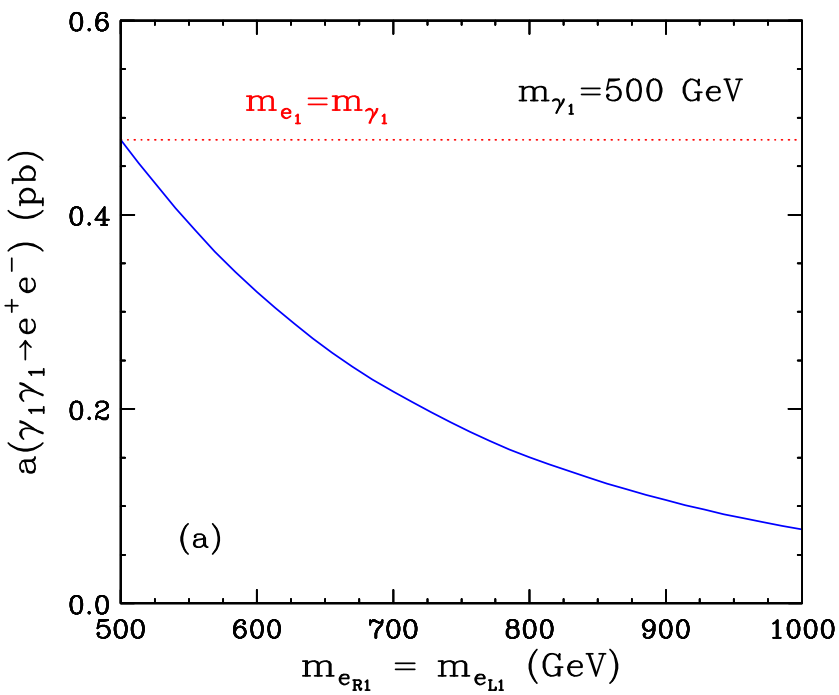
Relic Density Code

- Kong and Matchev (UF, 2005)
  - Fortran
  - Includes all level 1 KK particles
  - has a general KK mass spectra (all KK masses are, in principle, different)
  - can deal with different types of KK dark matter (γ_1, Z_1, $\nu_1 \cdots$)
  - improved numerical precision
    - use correct relativistic velocity expansion ($\langle \sigma v \rangle = a + b \langle v^2 \rangle$)
    - use temperature dependent degrees of freedom ($g_* = g_*(T_F)$)
- Servant and Tait (Annecy/ANL, 2002)
  - First code (γ_1 or ν_1 dark matter)
  - has cross sections in Mathematica, assuming same KK masses
  - use approximate relativistic velocity expansion
  - use approximate degrees of freedom ($g_* = 92.25$)
- Kribs and Burnell (Oregon/Princeton, 2005)
  - has cross sections in Maple, assuming same KK masses (γ_1 dark matter)
  - do not use relativistic velocity expansion
  - deal with coannihilations with all level 1 KK
- Matsumoto and Senami (KEK/Tokyo, 2005)
  - interested in resonance effects (γ_1 dark matter)

Assumption of mass degeneracy

(Kong, Matchev, hep-ph/0509119)

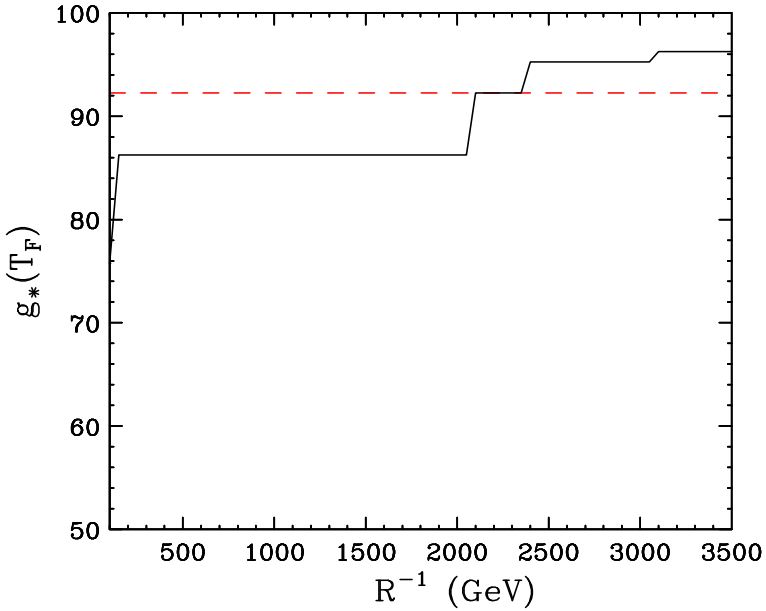
$$
\begin{aligned}
(ST)\,\sigma_{eff} &\sim \sigma_{11}(m_1) + \sigma_{1i}(m_1)exp(-x\Delta_i) + \cdots \\
\sigma_{eff} &\sim \sigma_{11}(m_i) + \sigma_{1i}(m_i)exp(-x\Delta_i) + \cdots \\
i &= \ell^1_R,\ \ell^1_L,\ q^1_L,\ q^1_R,\ g_1\ ,h_1,\ \cdots
\end{aligned}
$$



- Contradiction:
  - if $m_i \gg m_1 \Rightarrow \Delta_i = \frac{m_i - m_1}{m_1} \gg 1$
    $\Rightarrow \sigma_{11}(m_i) \neq \sigma_{11}(m_1)$
  - Different KK masses $\longrightarrow$ cross sections are too complicated to give in our paper
  - We expand to get a-terms and b-terms
- Assumption of exact mass degeneracy overestimates the corresponding cross sections and therefore underestimates the relic density
- For γ_1 self annihilation into SM fermions is shown in left

Temperature dependent g_*

(Kong, Matchev, hep-ph/0509119)



- The total number of effectively massless degrees of freedom

$$g_*(T) = \sum_{i=bosons} g_i + \frac{7}{8} \sum_{i=fermions} g_i$$

$$\Omega_\chi h^2 \approx \frac{1.04 \times 10^9}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{I_a + 3I_b/x_F}$$

- Large g_* underestimates $\Omega_\chi h^2$

Relativistic correction to b-term

- Relativistic correction to b-term
  - Non-relativistic velocity expansion used in Servant and Tait

$$\langle \sigma v \rangle = a + b\langle v^2 \rangle + \mathcal{O}(\langle v^4 \rangle) \approx a + \frac{6}{x} b + \mathcal{O}\left(\frac{1}{x^2}\right)$$

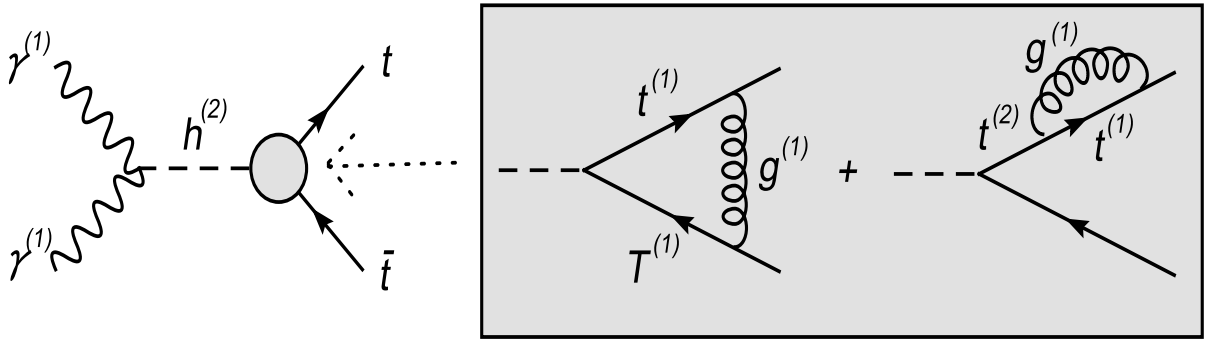
  - Relativistic calculation (Srednicki, Watkins, Olive, Nucl.Phys.B310:693,1988)

$$\langle \sigma v \rangle = a + \frac{6}{x}\left(b - \frac{1}{4}a\right) + \mathcal{O}\left(\frac{1}{x^2}\right)$$

- Non-relativistic velocity expansion underestimates $\Omega_\chi h^2$
- For γ_1 self annihilation:
  - $a = \frac{8\pi\alpha_1^2}{9m^2}\left(\frac{95}{18}\right)$, $b = -\frac{1}{8}a$
  - Correct b-term: $b - \frac{1}{4} = -\frac{3}{8}a$
- Numerically small correction but straightforward to fix

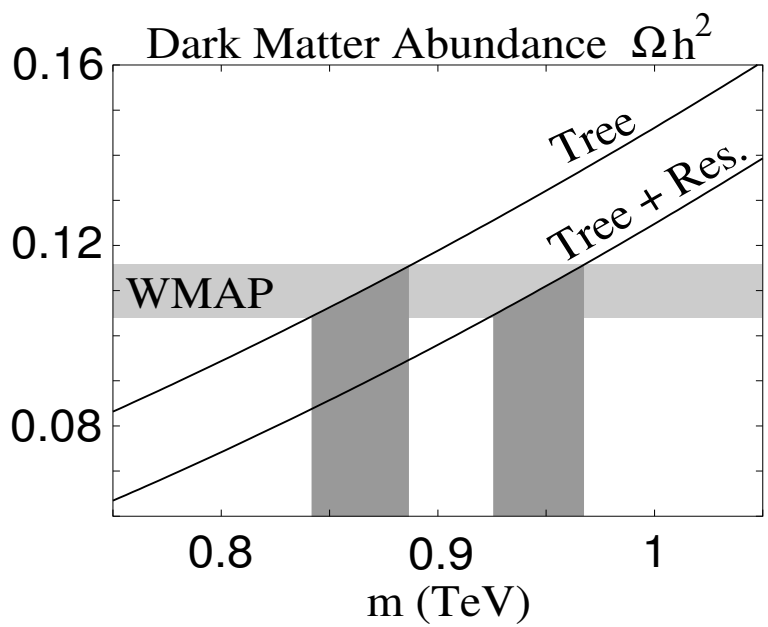
Resonant annihilation

- Resonant production increases cross section and decreases the relic density



- LKP mass increases by 100 GeV

(Kakizaki, Matsumoto, Sato, Senami, hep-ph/0204342)



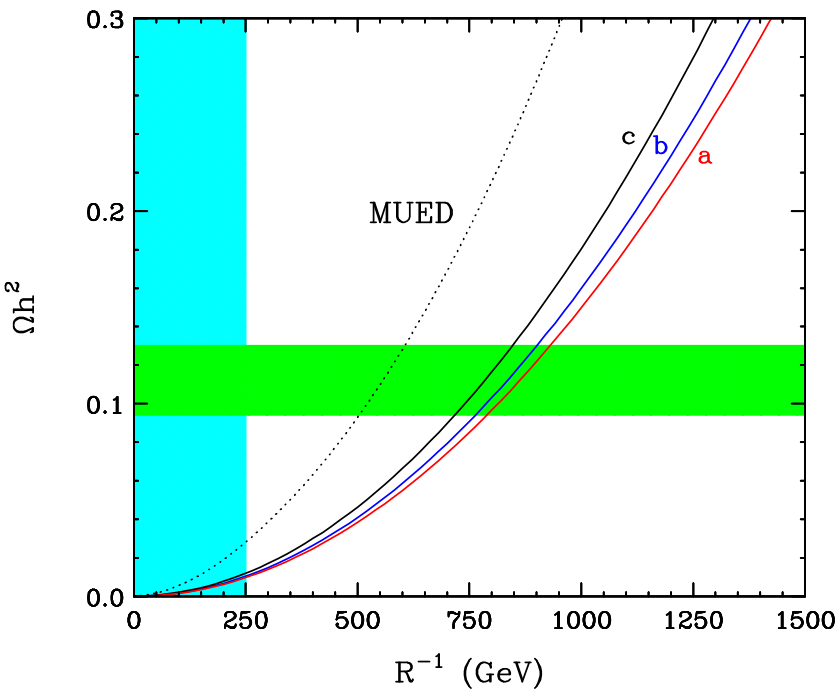
Our calculation

- Importance of other coannihilations in MUED
  - Mass degeneracy: $\Delta_i = \frac{m_i - m_1}{m_1}$
  - Coannihilations with heavy particles are Boltzmann suppressed $\longrightarrow$ you may think coannihilations can be safely neglected
  - But their cross sections are larger $\Leftarrow$ $SU(2)$, $SU(3)$ gauge couplings or top Yukawa couplings
- Beyond MUED
  - MUED makes an ansatz about the cut-off scale values of the so-called boundary terms
  - The boundary terms are not fixed by known SM physics
  - UED as a low energy effective theory with a multitude of parameters: MSSM
  - MUED as a simple toy model with a limited number of parameters: mSugra
  - Different ansatz $\longrightarrow$ different mass spectrum
    $\longrightarrow$ different phenomenology
  - Easy to find parameter space where other coannihilations are important
- Our calulation:
  - All coannihilations
  - Completely general mass spectrum
  - Numerical improvements

Improved result

(Kong, Matchev, hep-ph/0509119)

- Improvements in our calculation:
  - Include all coannihilations: many processes (51×51 initial states)
  - Keep KK masses different in the cross sections:
  - Use temperature dependent g_*
  - Use relativistic correction in the b-term

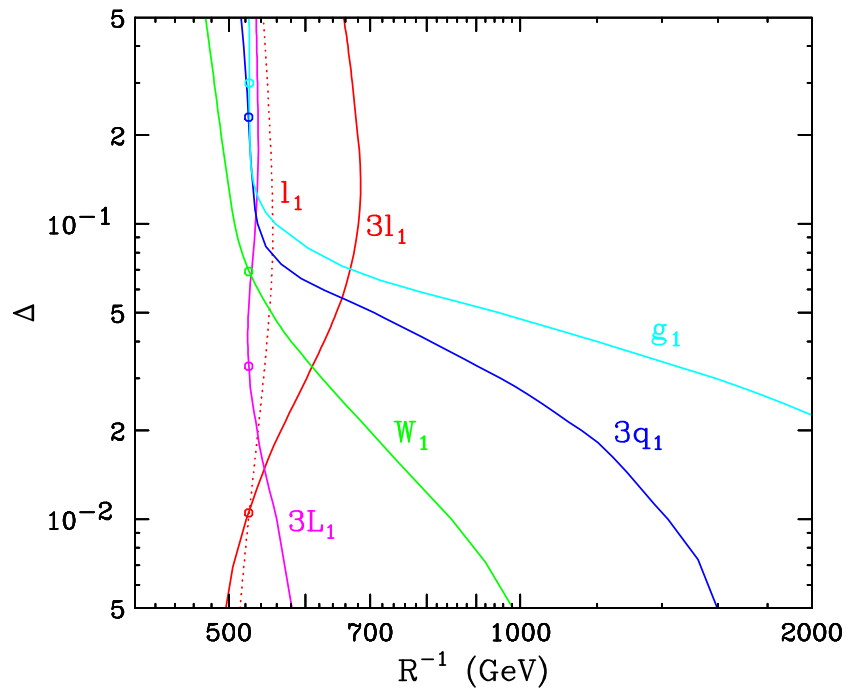


- a: $\gamma_1\gamma_1$ annihilation only (from hep-ph/0206071)
- b: repeats the same analysis but uses temperature dependent g_* and relativistic correction
- c: relaxes the assumption of KK mass degeneracy
- MUED: full calculation in MUED including all coannihilations with the proper choice of masses
- Preferred mass range: $500 - 600$ GeV for $0.094 < \Omega_{CDM} h^2 < 0.129$

Dark matter in nonminimal UED

- The change in the cosmologically preferred value for R^{-1} as a result of varying the different KK masses away from their nominal MUED values (along each line, $\Omega h^2 = 0.1$)

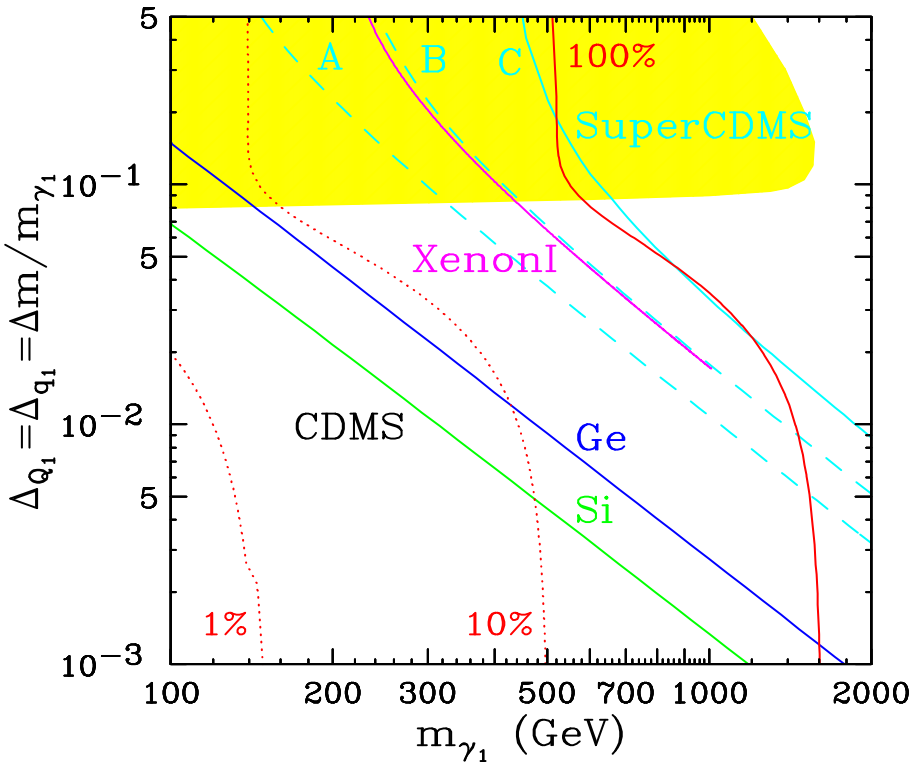
(Kong, Matchev, hep-ph/0509119)

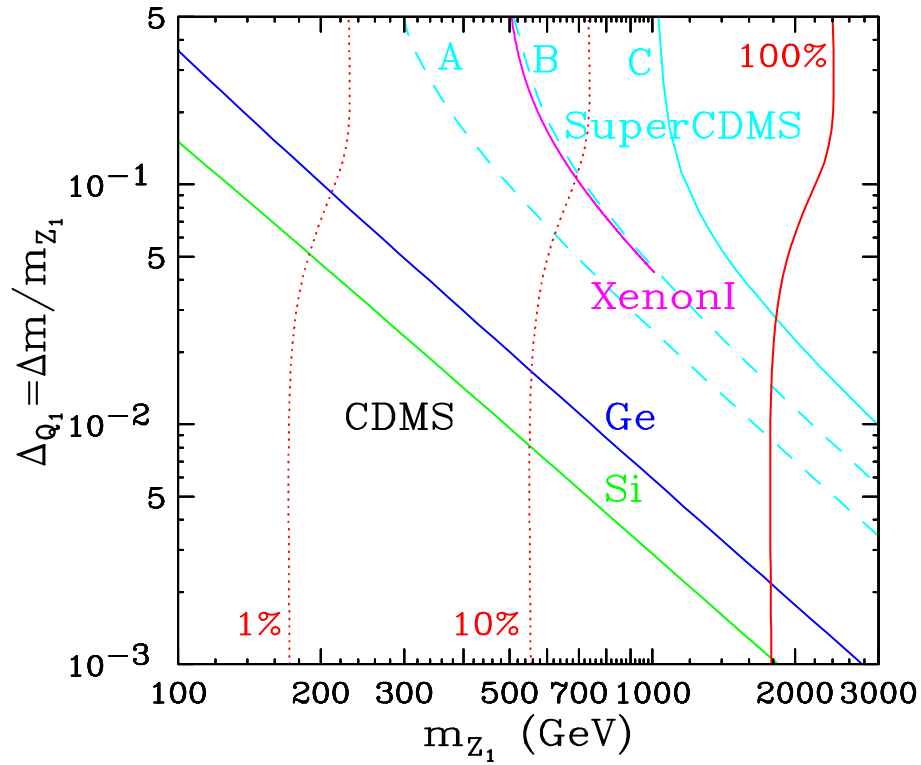


- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, m_{LKP} is large, UED escapes collider searches
    $\longrightarrow$ But, good news for dark matter searches

CDMS (Spin independent): B_1 and Z_1 LKP

(Baudis, Kong, Matchev, Preliminary)





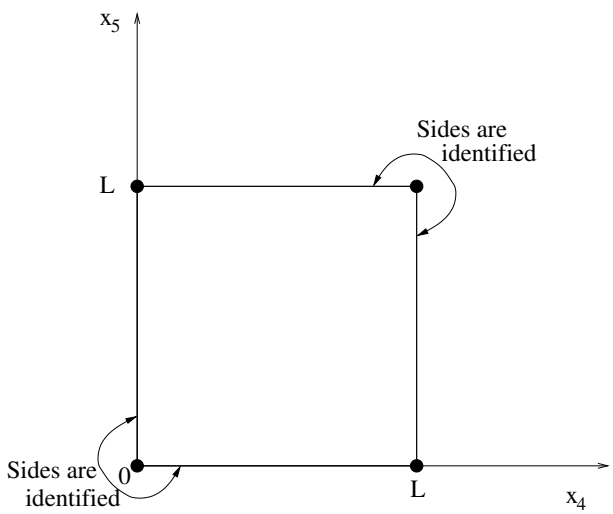
- SuperCDMS (projected)
  - A (25 kg), B (150 kg), C (1 ton)
- $\Delta_{q_1} = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$

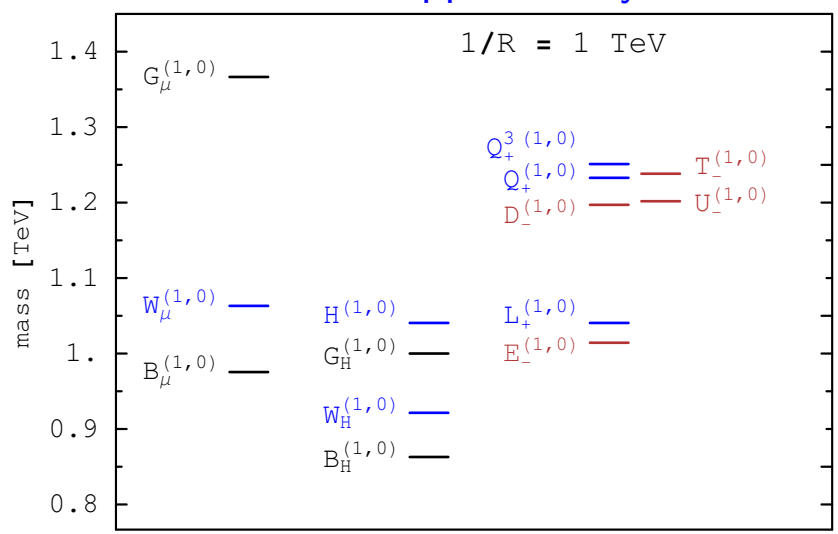
- Z1 LKP in nonminimal UED:
  - $\Delta_{Q_1} = \frac{m_{Q_1} - m_{Z_1}}{m_{Z_1}}$
  - $\Delta_{g_1} = 0.2$
  - $\Delta_1 = 0.1$

Two Universal Extra Dimensions on Chiral Square

- Motivation:
  - Possible to avoid proton decay (Appelquist, Dobrescu, Ponton hep-ph/0107056)
  - To cancel anomalies $\longrightarrow$ 3 generations (Dobrescu, Poppitz hep-ph/0102010)
- Chiral Square $\longrightarrow$ (n,m) KK-mode (Dobrescu, Ponton, hep-th/0401032)

  (Burdman, Dobrescu, Ponton, hep-ph/0506334) (Ponton, Wang, hep-ph/0512304)
- Different dark matter candidate: $B_H^{(1,0)}$ (Burdman, Dobrescu, Ponton, hep-ph/0601186)
  - $A_M^a = (A_\mu^a, A_5^a, A_6^a)$
  - $A_H^a \sim A_5^a - iA_6^a$ survives: a physical degree of freedom
  - $A_G^a \sim A_5^a + iA_6^a$ eaten: NGB
- $B_H^{(1,0)}$ self-annihilation: All fermion final states are suppressed by their mass

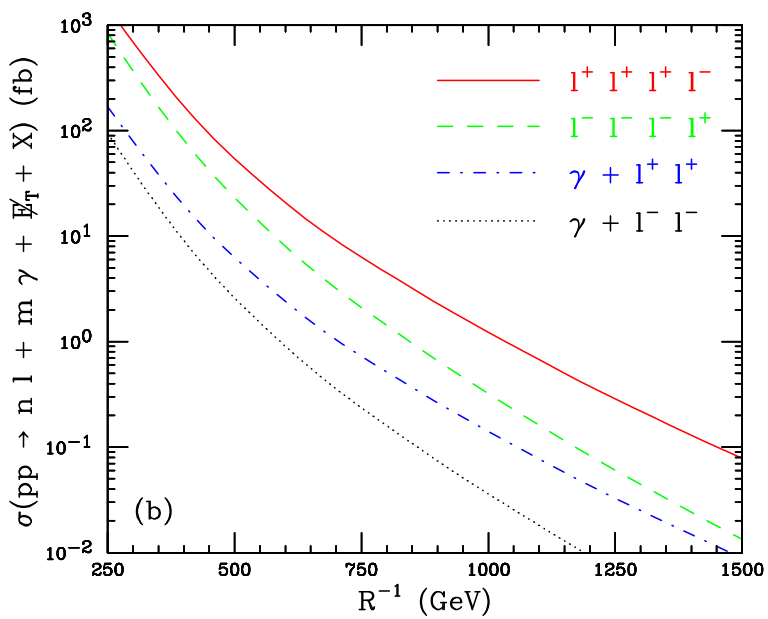


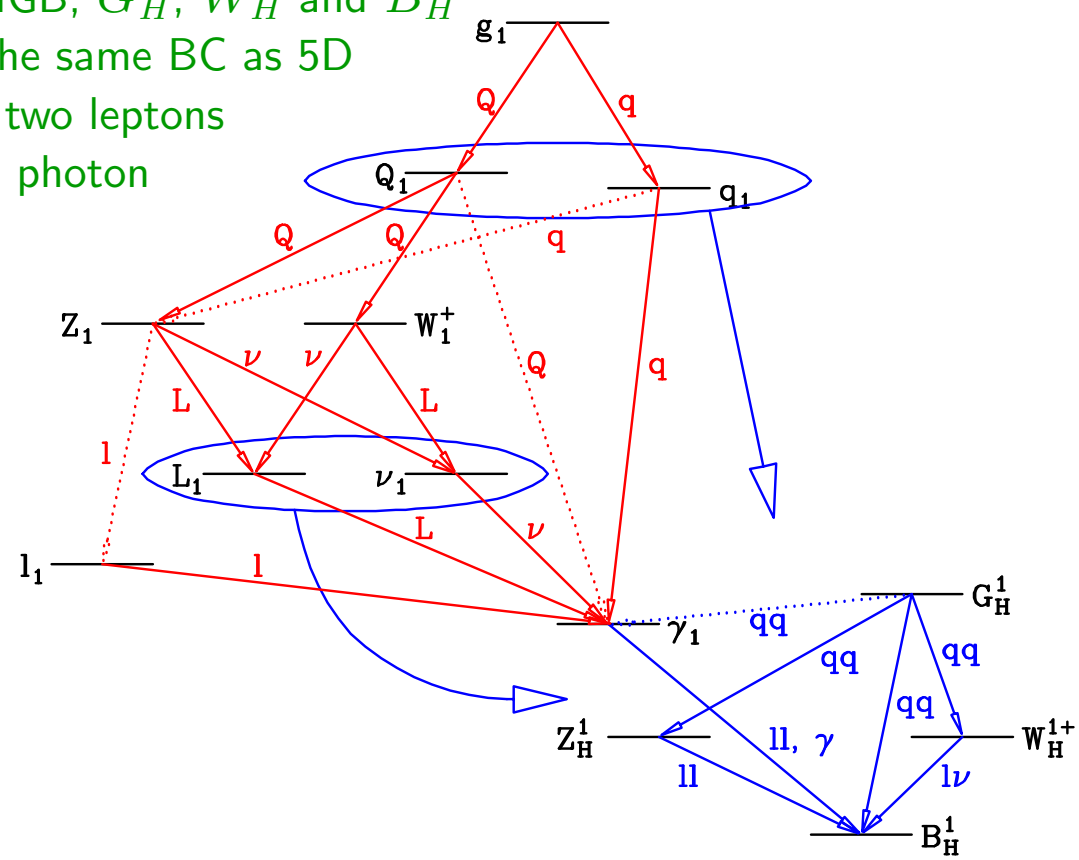


Leptons/Photons in Two Universal Extra Dimensions

(Dobrescu, Kong, Mahbubani, hep-ph/0703231)

- Explore different phenomenology: (1,0) mode with $M_{(1,0)} \sim \frac{1}{R}$
  - Spinless Adjoints: uneaten NGB, G_H, W_H and B_H
  - B_H: the lightest assuming the same BC as 5D
  - Tree-level 3-body decays $\longrightarrow$ two leptons
  - One-loop 2-body decay $\longrightarrow$ a photon
  - GMSB?

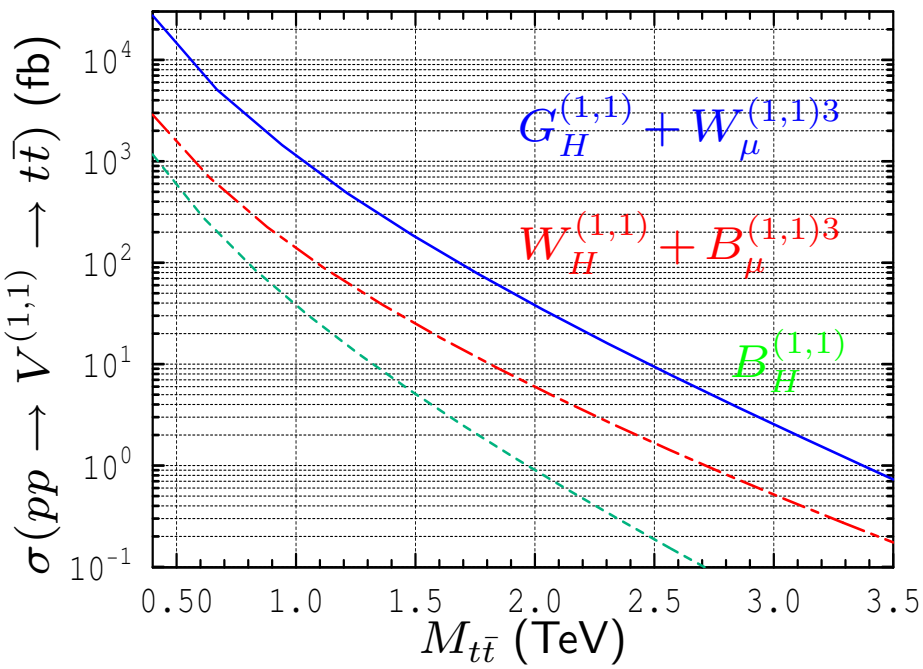




Resonances in Two Universal Extra Dimensions

(Burdman, Dobrescu, Ponton, hep-ph/0601186)

- (1,1) mode: $M_{(1,1)} \sim \frac{\sqrt{2}}{R}$
  - (1,1) mode is lighter than (2,0) mode
  - Three (neutral) gauge bosons: $G_\mu^{(1,1)}$, $W_\mu^{(1,1)}$, $B_\mu^{(1,1)}$
    - Loop-induced couplings $\longrightarrow$ lepto-phobic
    - $Br(W_\mu^{(1,1)},\ B_\mu^{(1,1)} \longrightarrow \ell^+\ell^-\,) \sim 1\%$
  - Three (neutral) spinless adjoints: $G_H^{(1,1)}$, $W_H^{(1,1)}$, $B_H^{(1,1)}$
    - Derivative coupling, $\bar{q}\gamma^\mu q \partial_\mu X_H^{(1,1)} \longrightarrow Br(X_H^{(1,1)} \longrightarrow t\bar{t}\,) = 1$
- 5 resonances in $t\bar{t}$: ($Br(G_\mu^{(1,1)} \longrightarrow t\bar{t}\,)$ is small)
  - But only 3 may be resolved:
    - $G_H^{(1,1)} + W_\mu^{(1,1)3} \sim 1.1\frac{\sqrt{2}}{R}$
    - $B_\mu^{(1,1)} + W_H^{(1,1)3} \sim 0.97\frac{\sqrt{2}}{R}$
    - $B_H^{(1,1)} \sim 0.86\frac{\sqrt{2}}{R}$
  - Top reconstruction?
  - Jet-energy resolution?
  - B-tagging?
  - A single bump with $\frac{\Gamma}{M} \sim 0.1$?



Summary and Discussion

- Extra Dimensions provide excellent dark matter candidates
- Coannihilations and mass degeneracy are important
- Spins of KKDM are different from that of (usual) SUSY candidate
  - 5D: B^1_μ, KK gauge boson (S=1)
  - 6D: $B^{(1,0)}_H$, spinless adjoint (S=0)
  - MSSM: χ^0_1, majorana (S=0.5)
  - GMSB: $\tilde{G}$, gravitino (S=1.5)
  - MSSM with $U(1)'$: $\tilde{\nu}$, sneutrino (S=0) (Lee, Matchev, Nasri, hep-ph/0702223)
- Collider signatures
  - 5D
    * Level 1: golden channel $\longrightarrow 4\ell + \not{E}_T$ (Cheng, Matchev, Schmaltz hep-ph/0205314)
    * Level 2: degenerate double gaussian di-lepton resonances (Datta, Kong, Matchev, hep-ph/0509246)
  - 6D
    * (1,0) mode: leptons and photons or multi-leptons (Dobrescu, Kong, Mahbubani, hep-ph/0703231)
    * (1,1) mode: $t\bar{t}$ resonances (Burdman, Dobrescu, Ponton, hep-ph/0601186)